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Ramirez, Jane Pauline; Hamaza, Salua

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Multimodal Locomotion: Next Generation Aerial–Terrestrial Mobile Robotics

*Jane Pauline Ramirez and Salua Hamaza**

Mobile robots have revolutionized the public and private sectors for transportation, exploration, and search and rescue. Efficient energy consumption and robust environmental interaction needed for complex tasks can be achieved in aerial–terrestrial robots by combining advantages of each locomotion mode. This review surveys over two decades of development in multimodal robots that move on the ground and in air. Multimodality can be achieved by leveraging three main design approaches: adding morphological features, adapting forms for locomotion transitions, and integrating multiple vehicle platforms. Each classification is thoroughly examined and synthesized, encompassing both qualitative and quantitative aspects. The authors delved into the intricacies of these approaches and explored the challenges and opportunities that lie ahead in pursuit of the next generation of mobile robots. This review aims to advance future deployment of multimodal robots in the real world for challenging operations in dangerous, unstructured, contact-prone, cluttered and subterranean environments.

1. Introduction

Aerial robots are mobile machines that have gained popularity due to their accessibility and expansive workspace. Among these, multirotors are distinguished by their compactness, agility, and versatility, which enable them to operate effectively in challenging environments. Despite significant technological advancements in aerial robotic autonomy, suboptimal energy management and limited payload capacities have constrained their practical applications. In contrast, terrestrial robots offer extended operational times, superior adaptability to environmental interactions, and greater payload capacity. However, they are constrained by challenging terrain that impedes their movement and hinders agile navigation.

J. P. Ramirez, S. Hamaza
Biomorphic Intelligence Laboratory
Faculty of Aerospace Engineering
TU Delft
Delft University of Technology
Kluyverweg 1, 2629 HS Delft, The Netherlands
E-mail: S.Hamaza@tudelft.nl

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Aerial–terrestrial robots are versatile mobile platforms capable of traversing both land and air. They achieve terrestrial movement through methods such as jumping, rolling, or walking, and aerial movement through gliding, hovering, and forward flight. These robotic platforms are found in various field applications including transportation, mapping and surveying, construction, media and entertainment, search and rescue, agriculture, and environmental preservation. Scientists have been actively researching different locomotion modes to gain insights into the mechanisms found in nature that enable multimodal capabilities and to uncover the tradeoffs inherent in biological systems to achieve such versatility.[1]

1.1. Historical Remarks

Decades of research have been dedicated to mobile robots with single locomotion modes. Terrestrial locomotion includes actions such as walking, running, hopping, snaking, two-anchor principle, peristalsis, rolling, and burrowing. Terrestrial mobile robots were previously classified into wheeled, walking/legged, tracked slip/skid, and hybrid categories.[2] The basic types of wheels analyzed in his survey are fixed standard wheel with one degree of freedom (DOF) rotating around the contact point; castor wheels with two DOFs rotating around a steering joint; Swedish wheels with three DOFs which revolve around the axle, contact point and rollers; and ball or spherical wheels for higher maneuverability. Aerial locomotion in animals includes flapping and gliding. Possible approaches to aerial locomotion have been presented[3] such as to provide lift: rigid wing, inflatable wing, or balloon; and to provide thrust: single rotor, birotor, coaxial rotors, or multirotor. A previous review of drones[4] categorizes different sizes of unmanned aerial systems into fixed wing, flapping wing, horizontal take-off landing, vertical take-off landing, tilt-rotor, tilt-wing, tilt-body, ducted fan, heli-wing, cyclo-copter, ornithopter, helicopter, and rotary wings. The latter can be further classified depending on the number of rotary propellers, from monocopter (helicopter) to dodecacopter, where the most adopted solution is the quadcopter.

In 2014, the first survey of biologically inspired multimodal robots was published[5] which covers a brief review of applications in hybrid environments. A detailed study on modes of locomotion in biology was presented to determine the trade-offs of multimodality in nature, embodied by different species of birds, reptiles, amphibians, fish, mammals, arthropods, and cephalopods, as well as in some multimodal robots. Fundamental principles of soft robot locomotion and the advantages and disadvantages were discussed previously.[6] In addition to crawling, legged locomotion, and jumping for terrestrial locomotion, flying, and swimming gaits, alternative modes of locomotion without biological counterparts were explained. Two categories were introduced: deformation-induced locomotion with tensegrity robots made up of rigid rods and compliant cables and vibration-based robots that use force direction variation and anisotropic friction. Another review which focused on the locomotion of miniature (μm to cm length scales) soft robots discussed several studies in multiple environments.[7]

In this work, general actuation principles that typically use smart materials are actuated by external stimuli. Technology limitations in the capacity of optimizing different modes of locomotion and in synthesizing capabilities are evident. A review of locomotion robo-physics gives a unique perspective of how physics can unlock real-world robot capabilities to tackle terrains that only self-propelled biological systems can traverse on.[8] It gives insight into using automation and simplification in understanding the robustness of engineered robots and living systems. They provided examples of analysis in challenging environments, including hard surfaces, terrestrial substrates, granular media, air, water, and the transition between solid and fluid. Moreover, computational tools and geometric mechanics were mentioned to explore motion experiments.

The earliest investigation of multimodal aerial–terrestrial flying/crawling insect-inspired robot was named Entomopter.[9] The design consisted of a fueled, reciprocating chemical muscle that powers flapping wings to generate lift and legs to crawl. This robot was intended for deployment on Mars and it is further discussed in Section 2. A decade later, the first adaptive design[10] transformed from a ground robot into a helicopter using coaxial counter-rotating rotors through folding mechanisms, as featured in Section 3. In the multivehicle assembly in Section 4, the first examples of aerial robotic carriers[11,12] were published in 2013 and 2014.

1.2. Aerial–Terrestrial Robotics Design Approaches

The capabilities of robots are determined by the specific requirements and constraints of the application. To integrate multiple modes of locomotion into a single robotic agent, engineers must initially comprehend the design and environmental limitations associated with each locomotion mode. In the subsequent sections, we delve into how existing prototypes have been developed using three primary design approaches: 1) Additive design: when the morphology of the robot remains unchanged while varying modalities; 2) Adaptive design: when robots are capable of altering their morphology (or morph) to traverse different domains effectively; and 3) Multivehicle design: involves the use of multiple vehicles working together to achieve multimodal functionality.

Figure 1 provides an overview of these design approaches, illustrating key concepts for each category. Additionally, **Table 1** summarizes the advantages and current limitations of each approach, shedding light on advancements and identifying general technological gaps. **Figure 2** references various prototypes representing these categories. The following stage of development involves the integration of multiple functionalities and locomotion types. Four hybrid domains, combining various modes of locomotion, are noteworthy: 1) Aerial–terrestrial: this domain, which is expanded upon in this review, combines aerial and terrestrial locomotion; 2) Aerial–aquatic: it features propulsion mechanisms that integrate aero- and hydrodynamics;[13,14] 3) Terrestrial–aquatic or amphibious locomotion: this mode, commonly found in nature and widely studied, combines terrestrial and aquatic locomotion;[15,16] and 4) Aerial–aquatic–terrestrial or trimodal locomotion: this versatile mode enables movement in all substrates.[17]

Aerial–terrestrial multimodal robots extend the capabilities of single-modal aerial and ground locomotion, enhancing their effectiveness in complex environments where individual modalities may impede performance during exploration phases. Here, we present nearly two decades of progress in the realm of aerial–terrestrial multimodal locomotion, furnishing a comprehensive and meticulous classification of prior designs, encompassing a total of 64 prototypes. We introduce these classifications to serve as a benchmark for assessing various locomotion strategies. Furthermore, we contemplate the forthcoming challenges and opportunities in the realm of designing and fabricating aerial–terrestrial robots, guided by their distinctive attributes, applications, and operational contexts. The overarching aim of this review is to boost the advancement and influence of aerial–terrestrial robots across diverse applications and environments.

To conduct this review, we rigorously scrutinized the Scopus, Web of Science, and Google Scholar databases employing the following keywords: "air-ground robots," "multimodal locomotion robots," "aerial-terrestrial robots," "fly-drive robots," "hybrid aerial-terrestrial robots," and "drones." It is important to note that this review expressly excludes software-generated illustrations or simulated results devoid of real prototypes and commercial platforms.

2. Monolithic Additive Design

We define monolithic additive designs as those single-entity robots that retain the overall body morphology when moving from one domain to the other. Additive strategy[18] incorporates the secondary ground locomotion mode via the use of additional actuators, mechanisms, or dedicated appendages that are not directly used in flight. In recent years, as control theory and mechanical design progress, more ingenious approaches have started to exploit physical design to transition from one mode to another. Monolithic additive designs are the most prevalent among the platforms.

2.1. Gliding Additive Designs

Flying animals in nature combine gliding and walking to reduce the cost of transport (energy) while extending the reachability envelope with a given energy stored.[19] Since this ability is commonly found in nature, engineers have used bioinspiration for their designs. Early implementations of multimodality-integrated gliding focused on its simplicity, benefiting from steady airflow conditions, and classical aerodynamic principles.[1]

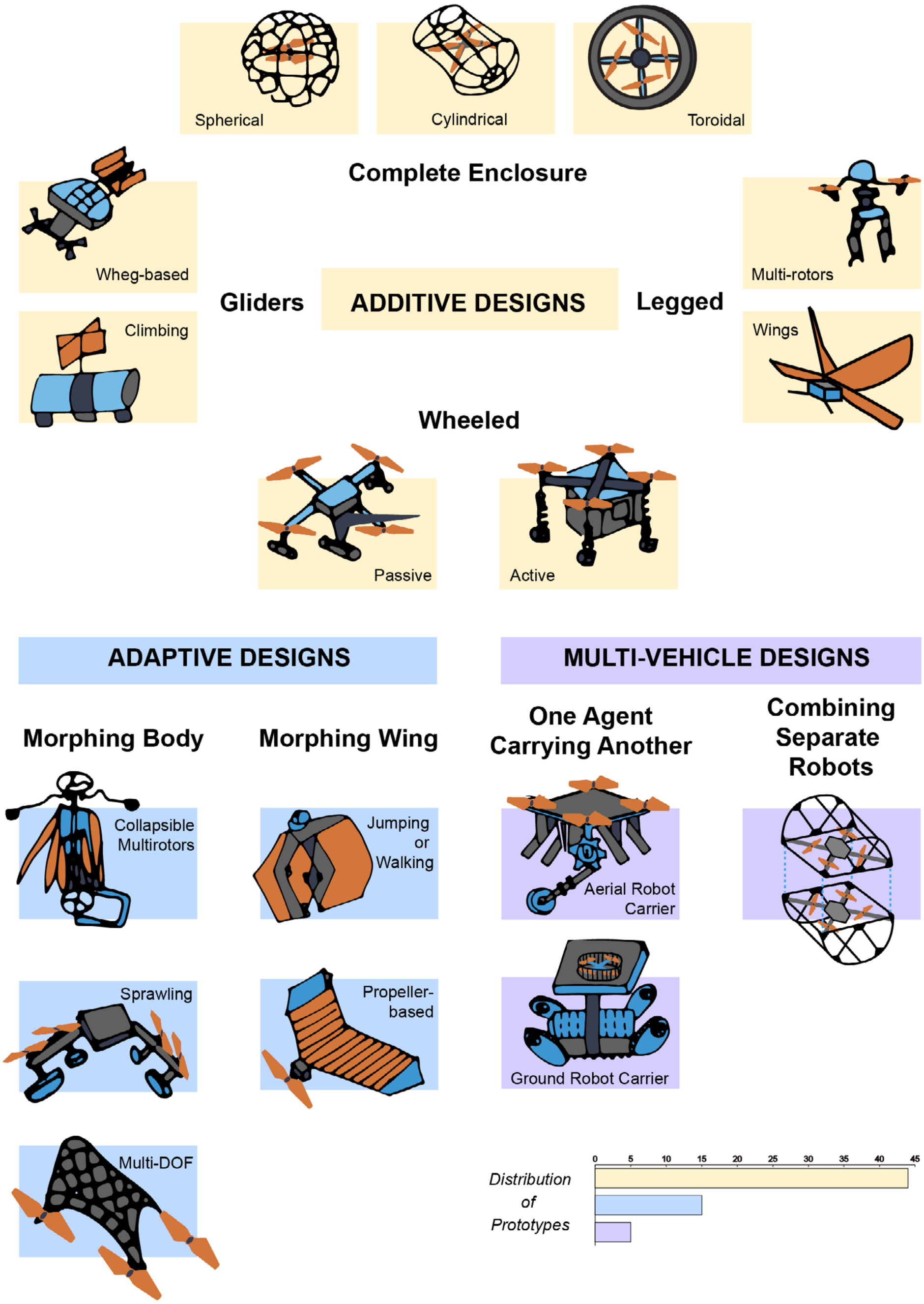

Figure 1. Overview of design approaches of multimodal robots with illustrations of some prototypes included in the review, namely: monolithic additive designs, monolithic adaptive designs, and multivehicle designs. Within each illustration, different parts are emphasized with highlights of black for the aerial components and blue for terrestrial components.

The main drawback of gliding is the lack of propulsion for powered flight.

2.1.1. Wheg-Based Gliders

In 2005, a platform capable of aerial–terrestrial multimodal locomotion could walk off the launch point, power dive, and walk again.[20] Two key points have led to this breakthrough. First, it exploited the use of flexible membrane airfoil found in microaerial vehicles[21] to increase stability while adapting to incoming flows and to delay stall that allows lower speed operation with a higher angle of attack. Second, it used bioinspiration to reproduce the mobility of cockroaches by using whegs, a combination of wheels and legs.[22] From this study, velocities are 5.5 km hr^{-1} or 3 body lengths per second on a thick lawn. Whegs are able to maintain relatively high horizontal velocity while keeping the

Table 1. Advantages, current limitations, and applications of different categories of multimodal robots.

Category		Subcategory	Advantages	Current limitations
Additive	Gliding additive	Wheg-based gliders	Low power consumption	Unpowered flight
			Ability to overcome obstacles and irregular terrain	Modeling complexity
		Climbing Gliders	Vertical climbing ability	Limited surface versatility modeling and control complexity
	Legged additive	Legged multirotors	Established field of legged robotics and mechanics	Low operational time
			Slacklining and skateboarding	Control, on-line state estimation, and modeling complexity
		Legged wings	Tunability of locomotion gaits especially with bioinspired designs	Limited to small scale due to heavy payload, efficiency and Power density or power charging requirements
	Wheeled additive	Passive wheels	Passivity minimizes additional weights and actuators	Low precision trajectory and controllability due to rolling inertia
		Active wheels	Increased controllability and faster transition	Power transmission mechanisms increase in weight and cost of transport
	Complete enclosure additive	Cylindrical cages	High damage resilience	Requires robust control and mechanisms for precise navigation
		Spherical cages	High damage resilience, disturbance rejection, manufacturability, decoupling solved using in-cage nested gimbals	Requires robust control and mechanisms for precise navigation
		Toroidal cages	Some damage resilience and low footprint	Requires more complex control algorithms for balance
Adaptive	Morphing body	Collapsible multirotors	High maneuverability and some degree of collision resilience	Need for high resilience-to-weight ratio materials
		Sprawling	Flexible height and center of mass adjustment	Modeling and control complexity
		Multi-DOF	Large configurability space	Modeling and control complexity and slow transition
	Morphing wing	Jumping or walking	Damage resilience	Robustness and usability
		Propeller based	Some degree of resilience and high maneuverability	High power requirement
Multivehicle	One agent carrying another	Aerial robot carrier	Independent units enable control distribution	Payload capacity and docking mechanism complexity
		Ground robot carrier	Independent units enable control distribution	Locomotion and docking mechanism complexity
	Combining separate robots		Redundancy and independence	High morphing complexity in mechanisms and control

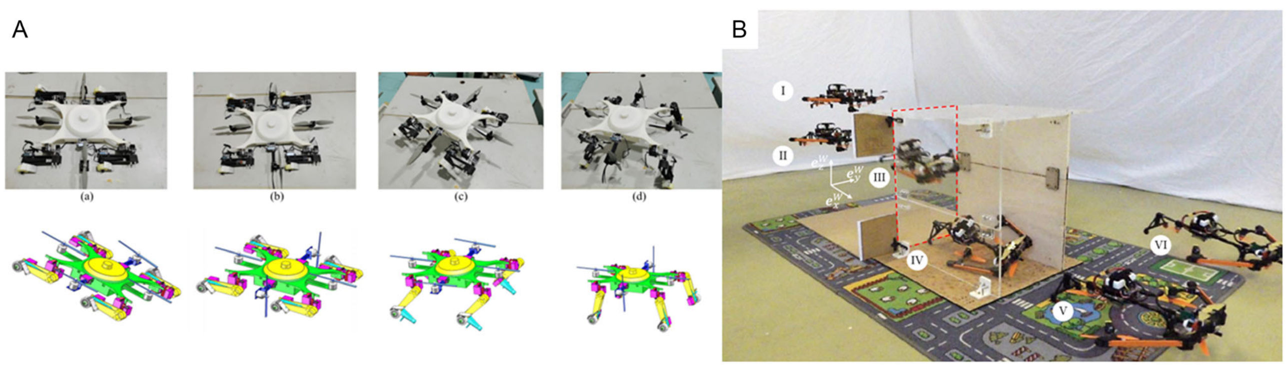

Figure 2. A) Triphibious-legged additive multimodal prototype changing modes: aerial, underwater, quadrupedal, and rolling. Size: 500 mm × 550 mm.[34] B) Multi-DOFs morphing body drone traversing a passageway. Nominal size: 420 mm × 420 mm × 126 mm Compact Size: 420 mm × 170 mm × 126 mm.[75] Reproduced under the terms of a CC-BY Creative Commons Atribution 4.0 International license, respectively: Copyright 2021, The Authors, published by IEEE;[34] Copyright 2022, The Authors, published by Wiley-VCH.[75]

control effort low (i.e., continuous actuation). However, minimizing the alternating movement perpendicular to the substrate brought about by the discontinuous spoke-to-ground contact decreases the ability to overcome obstacles. When the number of spokes is infinite, the wheg comes in the form of a wheel and the smoothness is favorable but the ability to overcome obstacles worsens. In contrast, when the number of spokes is minimum, it can handle obstacles better but worsens the smoothness.[23] Overcoming obstacles was achieved by high-stepping of front legs while the adjacent legs were 180° out of phase. Smaller versions with mini-whegs were significantly faster than most legged robots. From this point, compliance was added[24] in the four-spoke wheel-legs resulting in passive compliance in the wings, joints, and legs, achieving high air speed locomotion in flight and high-range locomotion on the ground. The micro air-land vehicle II has a cruising air speed of $11\,m\,s^{-1}$, a maximum flight time of 15 min, and terrestrial range of 0.99 km, with a wingspan of only 30.5 cm. Payload capacity is considered by utilizing strong lightweight materials such as carbon fiber. These specifications are useful for applications in surveillance, explosive detection, search and rescue, and remote inspection. Actual field tests demonstrated the value of adding modalities to single-mode robots. Adding semiautonomous capability and transmission mechanism tripled the weight[25] but improved impact durability (i.e., even after two crash landings, it was able to crawl successfully).

2.1.2. Climbing Gliders

A climbing robot that can glide[26] uses acrylonitrile butadiene styrene (ABS) skeletal fixed wings with wingspan of 760 mm wrapped with coverite microlite carbon-fiber reinforced foam and glider profile from balsa wood. It is small and lightweight and uses a Full-Goldman model[27] for vertical climbing bioinspired by insects and reptiles. The robot incorporates compliance on the feet for increased mobility on different surfaces, inspired by the flexible patagium of flying squirrels and flying dragons in the succeeding iteration,[28] with faster speed, i.e., vertical climbing speeds reached $13.5\,cm\,s^{-1}$ exceeding the previous platforms.

2.2. Legged Additive Designs

Walking multimodal robots are relatively few. Ground robots that walk with legs were equipped with either multiple rotors or a pair of wings to fly. Single-mode legged designs can operate effectively in unstructured, rough terrains, but weight becomes a limiting factor when transitioning to flight.

2.2.1. Legged Multirotors

Passivity has been harnessed in an underactuated drone, as discussed in Pratt's work.[29] This approach utilizes two passive legs for terrestrial locomotion on flat surfaces, coupled with quadcopter rotor thrust for ascending and descending gentle slopes. The passive legs, being unpowered, eliminate the need for an energy source during terrestrial movement. A recent milestone in robotics, exemplified by the bipedal robot,[30] employs two propellers for both aerial and terrestrial locomotion stabilization. This robot, named LEO, stands 75 cm tall and weighs 2.58 kg, featuring dynamic control and an anthropomorphic leg design that allows it to perform activities like walking on a slack line and skateboarding. Adding additional legs to a robot can enhance controllability across various applications. In the case of a quadcopter equipped with four active terrestrial legs,[31] each leg is actuated with two linear actuators, employing a three-spherical-prismatic-revolute parallel manipulator. This design achieved a maximum walking speed of $65\,mm\,s^{-1}$, enabling the quadcopter to take off, fly in open spaces, and even walk on grass. However, the augmentation of limbs to enhance controllability often introduces higher drag, impeding movement. Solutions have been proposed, such as stowing propellers on the legs during ground movement[32] or employing flexible leg components during flight.[33] It is worth noting that these modifications can increase the moment of inertia and, consequently, the energy required for actuation in the alternate mode of locomotion. Additionally, some innovative approaches have emerged, such as the development of a triphibious prototype, which combines wheels and four legs attached to a conventional quadrotor drone with tilt-rotors.[34] Furthermore, miniature multimodal robots with epoxy/fiberglass laminate construction have been implemented, allowing for crawling and gripping capabilities.[35]

2.2.2. Legged Wings

Naturally, insects and birds are used as bioinspiration sources for this category. Winged drones with legs are usually less than few tens of grams in weight. The earliest investigation of multimodal aerial–terrestrial locomotion specifically a flying/crawling insect-inspired robot named Entomopter from Georgia Institute of Technology with patent published in 2000.[9] The design consisted of a fueled reciprocating chemical muscle that powers the flapping wings to generate lift and legs to crawl intended for flight on Mars. Typically, electromagnetic motors connected to linkage mechanisms to convert rotary to oscillatory flapping motion are utilized.[36] However, conventional motor efficiencies and power densities decrease with size. Therefore, most of the power budget in designing these robots is allocated to maintain altitude airborne, rather than controlling surface actuation.[37] This implies that small-scale robots have very limited mobility autonomy. Moreover, fabrication on smaller scales is complex and needs novel materials and techniques to overcome these challenging scaling effects. For example, a 74 mg robot[38] uses piezoelectric actuators to extend movement to water surface locomotion. Early implementation of a bipedal ornithopter capable of running with two flapping wings[39] weighing less than 12 g is made of carbon fiber and polyethylene terephthalate. Similarities in techniques for designing macro-sized drones are also apparent. Drones could integrate ground robot hexapedal design[40] into wings and introduce compliance to tune stiffness, thereby achieving multiple gaits through direct drive or via transmission mechanisms.

2.3. Wheeled Additive Designs

The most common approach to add terrestrial locomotion to an existing flying platform was by adding wheels. A propeller-based drone was equipped with wheels that could be driven passively or actively. Some wheeled designs also employ propeller cages[41–43] for collision tolerance to prolong the usable life and improve robustness. These drones have a partial enclosure in the form of cages protecting the set of propellers and motors. Complete enclosure designs are further discussed in the next subsection.

2.3.1. Passive Wheels

Typically, passive wheels are added to quadrotors and birotors and exploit the propulsion from the propellers to move and steer on the ground. This is favorable because the coupled actuation of flying and moving might prevent additional weights and motors. A passive wheel design incorporated a skateboard truck wheel mechanism with a quadrotor.[44] This simple, robust 1.3 kg platform used three pairs of two parallel soft foam-rubber wheels with low-friction roller bearings. This is the only design that elevates the middle pair of wheels, while the other pairs in each of the two ends remain on leveled ground. However, this design was intended only for smooth rolling surfaces that are not usually available in field applications. Additionally, no brake system is present, nor any sensor suite for obstacle avoidance and localization, preventing deployment in the field. Additional tests are needed to make this vehicle more controllable such as examining the coupled yaw and raw mechanics in extreme turns and testing in highly sloped ground.

The simplest way to make multimodal drones is by adding wheels to quadrotors. Two tiltable axles and four passive independent wheels provide locomotion efficiency, payload capacity, wall-climbing capabilities, and the ability to move on rocky uneven soil ground.[45] Four wheels could be added to a quadcopter fixed to the main body using acrylic sheets with dampers in between wheeled multirotors integrate autonomous collision avoidance in flight and on the ground to maximize multiterrain operation.[46] However, using rigid materials for stabilization limits possible application in unstructured environments and adds weight. With the same number of wheels and propellers, precise locomotion such as in takeoff can be also implemented using deflectors,[47] which may even be extended to aquatic environments. Although deflectors add air resistance and weight, this concept also enables multimodality, and adding a mechanism for grasping enables manipulation. Miniaturizing drones, with scaling challenges previously discussed, can also be implemented using off-the-shelf products such as Crazyflie drones with two small passive wheels making fabrication simple.[48] Additionally, the diameter can be enlarged and the width of the wheel can be decreased to lower contact friction. With this, wheels protect propellers from the sides of a quadrotor[49,50] and a birotor vertical takeoff and landing drone.[51] Instead of lateral protection, partial enclosure of drones using propeller cages, typically in spherical shape can act as wheels, giving protection to propellers from all sides and further improving impact resilience and longevity in quadrotors[41,43] and birotors.[42]

2.3.2. Active Wheels

Innovations when using active wheels in transitioning from rolling to flying and vice versa, often take ideas from automotive design and ground mobile robots. The most common approach is to add four wheels to a quadrotor.[52,53] Unlike passive wheels, actuated wheels have motors and power transmission mechanisms, e.g., gears or belts, that increase weight. Therefore, using lightweight materials is crucial for longer operation times, since flight time is severely affected by mass increases. The tradeoff of increasing controllability by adding active wheels is the increased cost of transport while flying seen evidently on the resulting sustained operational time of only a few to several minutes (i.e., sustained time in ground mode: 3 h vs flight mode: 5 min).[52] In the study of Tanaka et al.,[54] a stabilizer that acts as additional support equipped with a passive wheel is a possible mechanical solution to precise control. This is added to recover from flipping after breaking but this also adds weight. In contrast, these problems emphasize the potential of multimodality as it increases the overall operational time by adding a ground mode that sustains movement for a few hours under the same power source. This was shown in experiments such as breaking tests (≈18× in distance), turning tests (≈3× in time), and stability tests (max slope angle comparisons) done to verify improvement by the stabilizer.[54] Adding suspensions using springs to omnidirectional wheels[55] can be potentially applied to rough terrains. Propeller cages as actuated wheels can be used in unknown environments and drones can further benefit from the use of mapping, planning, and autonomous navigation.[56] Using active wheels mitigates perception degradation in dusty environments due to downwash from thrust. While propellers are in a fixed position, tilt-hovering that enables flight speed control by changing thrust direction could also be implemented to control position and altitude independently.[57] This increases visible sensor range (can exceed 180 with tilt-hovering in the platform) and reduces blind areas, as well as reduces energy loss by lowering air resistance by arranging the wheels. In this case, even if the system is underactuated, linear dynamics is decoupled from rotational dynamics. This was implemented on a drone with two coaxial rotor drones as well, each actuated by a brushless direct current motor, with three actuated ball rollers in a triangular arrangement for wheels.[58] However, additional actuation adds degrees of freedom thus adding complexity to control.

2.4. Complete Enclosure Additive Designs

Complete enclosure designs protect the whole body of the robot, thus giving the best resilience against collision and damage. High strength-to-weight ratio carbon-fiber reinforced plastic is typically used as material for enclosures. Commonly, complete actuator coupling of the propellers and cages[59] is implemented or the enclosure is decoupled via a gimbal.[37,60] Enclosures can be cylindrical, spherical, or toroidal. Collision resilience is typically the main reason behind enclosed designs, more so because the ability to roll can be challenging to embed in these configurations: the orientation and rolling motion mechanisms are linked in complete enclosure drones, therefore preferential kinematic rolling directions exist that generate constraints that can be expressed as an equation relating other coordinates.[61] These pose a challenge to trajectory tracking on the ground. Moreover, scaling up the size of the enclosures increases both weight and drag in flight. Lastly, encumbrance structures can occlude the sensors attached to the robot.

2.4.1. Cylindrical Cages

Protectors in cylindrical shape can make contact with surrounding environments while avoiding interference with visual sensors embedded in the core. A design features a quadrotor with a cylindrical cage connected to a bearing that enables single-axis rolling forward and steering via differential propeller forces.[59] In this particular work, brushless motors drive the propellers for 27 min on the ground and 5 min in flight. Varying mechanical connection is also done to simplify dynamics and control in the succeeding prototypes. A spokeless two-wheeled drone with a cylindrical cage climbs and runs on a bridge.[62] This design minimizes the damage of lightweight wheels used with multirotors during collision, falling, or landing.

2.4.2. Spherical Cages

To address the holonomic constraints or conditions that can be expressed as relations between coordinates of cages as imposed by the robot structure when rolling, a few works have decoupled the multirotor from the terrestrial rolling mechanism by using nested gimbals inside the cage.[61,63] Experiments showed that the tangential coefficient of restitution is significantly lower for the freely rotating gimbal system for almost all cases.[60] In doing so, the rolling motion perturbation is minimized when the robot interacts with the environment. One example of a microspherical rolling and flying robot is[64] designed with a quadcopter enclosed by combined two steel wire half spheres, with a 3D-printed carbon fiber axle, and transition experiments were validated using curved rolling trajectories.

2.4.3. Toroidal Cages

Toroidal cages are cages with narrow widths that act like ring-shaped structures. Since they have narrow bodies, they have less aerodynamic impact and are better suited for navigation in tight spaces or in cluttered environments. These enclosures act as protection in two ways: 1) they provide resilience to propellers in lateral collisions; and 2) they enable landing and rolling with a minimal footprint. Aerial drones equipped with variable pitch propellers[65,66] can also have partial enclosures using toroidal cages. For example, a passive reconfigurable airframe can be enclosed by a narrow cage made of carbon fiber sheets and rods.[65] Also, a monowheel that can stand on the ground and roll has three DOFs with propellers that enable inverted flight.[66] This drone can also traverse air, land, and sea for disaster response. The inclined and vertical rolling capabilities enable traversing narrow gaps at an angle and uneven terrain. A similar idea is employed to[67] a thinner unicycle wheel to roll and traverse through narrow gaps while using quadrotors to fly over obstacles.

3. Monolithic Adaptive Design

The adaptive design is inspired by nature, in animals' ability to change their shape or form, as a response to stimuli. This integrated design strategy, also known as metamorphic, shape-shifting, or shape-morphing, entails a complex tradeoff in multimodal capabilities but has the potential to optimize the overall performance in both modes. Most of the metamorphic aerial–terrestrial prototypes analyzed are propellers-based with morphing abilities for narrow traversal or they implement variable height adjustments. Some works feature wings that can glide, enhance lift, or protect propellers.

3.1. Morphing Body

Morphing body drones are compact robots with components that fold and unfold, squeeze or collapse, or reorient while transitioning to another locomotion modality.

3.1.1. Collapsible Multirotors

Similarly to a tail-sitter aircraft, a two-wheeled ground robot transforms into a helicopter using coaxial counterrotating rotors, enabling it to overcome obstacles and rough terrains.[10] Transforming to a different mode happens through the folding of the landing gear mechanism, but the aerodynamics, efficiency, and energy storage of the drone limit the morphing capability. A similar drone focused on improving the ground ruggedness and maneuverability by stowing flight components while in ground mode through gear connections and linkages.[68] Following these approaches of stowing propellers, automatic mode shifting with 3D planning and tracking was demonstrated to perform in indoor and outdoor environments.[69]

3.1.2. Sprawling Morphing Body

Sprawling is a concept translated from biology that utilizes the wheel-linkage mechanism and leverages active transition. In sprawling, the robot morphs by extending and retracting its arms or limbs, thus altering its configuration and the relative height of its center of mass.[70] Partial actuator coupling where a set of wheels or appendages is active and another passive is employed in this design. The front wheels are passive while the back wheels are active. The next iteration[71] exploits thrust in the downward direction to crawl up steep slopes and walls and to ease rolling on uneven terrains, e.g., over grass and small stones.

3.1.3. Multi-DOFs Morphing Body

A unique shape-morphing soft exoskeleton made of kirigami meta-materials can reversibly transform to transition into different modalities using temperature control.[72] This work remarkably exploits various principles of intelligence via the integration of smart materials to achieve multi-DOFs metamorphosis.[73] A recent work[74] reports on exhaust appendage redundancy manipulation through morphing to achieve locomotion plasticity. The four legs were repurposed for quadrupedal locomotion, thrusters for flight, moving through slopes, tumbling over large obstacles, loco-manipulation, crouching, and two-wheel and four-wheel locomotion. Other examples of multi-DOFs morphing bodies combine the features of a foldable frame, typically compliant and autonomous navigation to traverse narrow passages in the transition from rotor propulsion to wheels[75] or tracks[76] when in contact with walls.

3.2. Morphing Wing

Flying animals use their flapping appendages or wings for powered flight. Additionally to obtain lift, a membrane or fold of skin called patagia spans both sides of the body increasing the surface area. They commonly use fore legs to explore by crawling or walking and hind legs to do escape maneuvers. Mammals, such as bats, have flapping patagia; while squirrels or lemurs have extended digit formation that maximizes the surface area within the expanded patagia.[5] Other flapping-wing mechanisms enable lift in birds and insects.

3.2.1. Jumping or Walking with Morphing Wing

Aerial robots that combine jumping and walking can perform multiple trajectories in the landing phase, which can be helpful to minimize damage at impact. Four-bar linkages, cables, and springs enable robots' legs to lift off in jumping, reaching heights of three meters, before starting the gliding phase.[77,78] In the study of Shin et al.,[79] a bioinspired gliding and walking robot utilizes a flexible membrane airborne and has optimized legs with variable-torque joints to adapt its shape in both locomotion modes and to enable multiple gait patterns on the ground inspired by flying squirrels. The robot has four legs with three servo motors in each leg and one motor for tail. Although this needs to be hand-launched, it can glide at a high angle of attacks through membrane and tail control, it can land safely and then walk. However, stable walking and gliding were only experimented indoors using a motion capture system. Using wings also increases the range in jumps from elevated positions and it steers gliding flight.[80] Jump-gliding increased the horizontal distance traveled in the experiments by 123% than with jumping only. Accurate theoretical models of the jump-glide envelope for nonequilibrium flight dynamics can further improve the gliding ratio in robot designs. The addition of wings increases aerodynamic lift, improving performance but hindering efficiency due to the extra mass.

3.2.2. Propeller-Based Morphing

Wing bioinspiration can be used with an adaptive approach to design drones for long-distance flight and local exploration in cluttered environments. Integrating actuators via coupling is convenient when the aerial and ground mode dynamics lie within the required operational range of each locomotion. This can reduce total complexity and weight. Wingerons are wings assisted by propellers that integrate both modes by generating lift for flying and rotating about the frontal axis for walking.[3] In contrast, an insect-inspired drone with wheels and propellers[81] made of expanded polypropylene foam, plywood, and ABS, can be protected by foldable wings. Adding wings enhances the lift and impact resilience but it causes the weight to increase.

4. Multivehicle Assembly and Cooperation

Within this strategy, each robot has its own propulsion and energy source, and multiple vehicles can combine or cooperate as a unit. Designs of seamless docking, grasping, and releasing mechanisms are crucial to attach and detach entities together and ensure mechatronic integration. Multivehicle multimodality can be applied to disaster sites exploration for rapid search of victims because combining different robot abilities satisfies deployment categories for urban search and rescue.[82] However, integrating multiple robots together results in high complexity in control and actuation, hence for multimodal multivehicles robots, perception is a crucial aspect.

4.1. One Agent Carrying Another

If a multimodal combination consists of at least one air and one ground robot, the decision to assign a primary vehicle to carry the other depends on the payload capabilities and the task requirements. Ground robots have higher operational time and payload capacity than their aerial counterparts, making them the favored carrier modality. In contrast, aerial robots have an unbounded workspace to move, only limited by the energy source.

4.1.1. Aerial Robot Carrier

When the aerial robot carries, either the robot has a high payload capacity or the carried ground robot is very lightweight and compact. Integrating a lightweight ground-wheeled snake-like robot on an aerial robot was done via a passive magnetic docking system.[12] In ecology monitoring applications, a hexarotor carrying a small ground robot was teleoperated for volcanic ash observation. The ground robot can climb slopes and drive in overturned state with four wheels.[11] Both robots are equipped with identical global positioning systems and communication systems. The risk of damage upon release of the ground robot is dependent on the height control of the flying vehicle, which becomes difficult in deployment over uneven terrains.

4.1.2. Ground Robot Carrier

Since ground robots have higher payload capacity than air robots, ground robots may act as a primary agent that carries. Two tracked ground platforms and a quadrotor can be combined for earthquake-damaged building mapping.[83] Each ground robot provides odometry with laser scanners and inertial measurement unit (IMU) information. Stabilizing arms enable stair climbing and navigating in cluttered environments, while the off-the-shelf quadrotor was equipped with an IMU and a pressure sensor. Coordination is also possible on small scale (less than 50 g in total) where a flapping wing ornithopter micro-aerial vehicle can collaborate with a millimeter-scale robot that can act as a launching platform.[84] Experimental results show that embodied integration of the flapping of the ornithopter increased the velocity of the ground robot by 12.7% and independent cost of transport decreased in comparison to separate independent robots.

4.2. Multirobot Assembly: Combining Separate Robots

When separate robots operating as independent physical entities morph together into one entity they become a multirobot assembly. An example of a cooperative aerial–terrestrial robot features multiple multicopters enclosed in semicylindrical shells that dock together using permanent electromagnets along their frames. The resulting morphology is a flying-rolling robot that moves on the ground using integrated thrust control from two sets of four propellers.[85]

5. Challenges and Opportunities

Compared to single-mode morphologies, the additional functionalities offered by multimodality come with increased design and control complexity. In this section, we discuss challenges and opportunities for multimodal robots with the following subsections summarized in **Figure 3**: locomotion, nature intelligence, mechanical design, materials and manufacturing, mechatronics, modeling, control, manipulation and teleoperation, and performance metrics. Operating over multiple domains or media often causes conflicting design requirements, namely: 1) additional mechanisms for ground locomotion versus increased weight for flight payload; 2) exploiting passivity in suspension system versus designing more active resilience using control and more actuators; and 3) adaptation versus implementation complexity in development and testing.

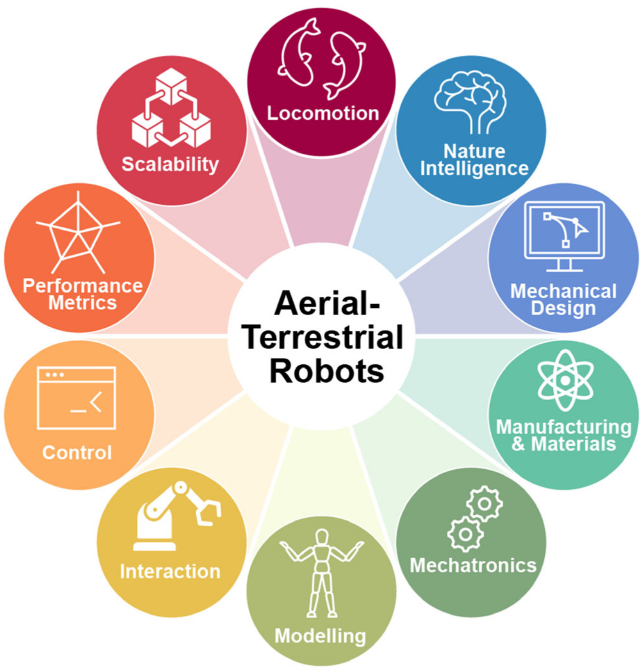

Figure 3. Challenges and opportunities for multimodal aerial–terrestrial robot development.

Optimal parameters can be obtained for specific applications or performance requirements. These include versatility, maximum wingspan, maximum payload, control stability, transition smoothness, robustness, dynamic balance, low risk of failure, resilience in harsh environments, reconfigurability, structural integrity, impact resilience, center of mass optimization, stable gliding, optimal angle of attack, obstacle detection and avoidance, higher payloads, high response time, high operating time, propeller efficiency, mechanism actuation response time, ability to move up inclines, aerial gliding, flapping flight, durability, compactness, small landing footprint, self-recovery, and self-uprightness.

5.1. Locomotion

In this review, we have presented robots that can walk, run, roll, crawl, go up an incline, land, wall-climb, adhere to ceilings, glide, jump, flap, hover, take off, and even skateboard and slackline. Nature inspires other modes of locomotion to be combined and integrated together to achieve task requirements in specific scenarios. In search and rescue applications, multimodal robots are tasked to traverse cluttered and confined environments, such as disaster sites, wet and dry landslides; slippery, brittle, or debris-filled terrains; high altitude or high-risk areas such as rooftops, bridges, or ledges.[82] Space applications include unstructured, dusty, and rocky areas in planetary explorations. Other challenging environments include forests with a high density of obstacles, narrow passageways, low light, and high humidity.

Animals have an inherently higher degree of morphological intelligence within a compact encumbrance of sensors and muscles that enable them to perform complex actuation tasks with great versatility. In robotics, combining physical intelligence and computational intelligence is key to push performance and bring prototypes to higher field readiness, analogous to their biological counterparts.[86]

5.2. Nature Intelligence

Morphing abilities in insects have very low response time due to their efficient proprioceptive assets distributed in the body and brain, that almost act as a sixth sense in response to external stimuli. Animals can camouflage, thermoregulate, control humidity, and control passive flight stability. Changes in chemical properties are used for adaptation to challenging and hazardous environments. If engineers were able to embody this type of intelligence into compact and lightweight electronics,[87,88] we would experience considerable advancements in real-time control and actuation, for multimodality and beyond. This opens questions in multiple fields of science, especially in biology and experimental zoology. Embodying intelligence requires a deep understanding of animals' abilities with creative design and experimentation. Roboticists, in contrast, require accurate modeling of robots that verifies translation of concepts. With scientific inquiry, we can start with the traditional design of machines and robots which involves a recursive process of conceptualization, sizing, implementation, and testing.[89,90] To come up with reliable working prototypes, bridging multidisciplinary concepts with scientific experiments requires persistent curiosity and knowledge transferability.

5.3. Mechanical Design

Aerial–terrestrial robots' morphology greatly affects aerodynamics and ground locomotion efficiency. It determines performance, resilience, flight range, and geometric adaptability in various spaces. Varying shapes can improve lift and drag ratios, especially in wing-based robots. Taking inspiration from animals' abilities and integrating principles into rotor design, gliding, flapping-wing-based flight, or other propulsion modes, may increase flight efficiency. Adaptive landing gear systems can be incorporated into the locomotion mechanisms. Reverse thrust capabilities extend the functionality of wall climbing and ceiling rolling multimodal robots.[91] In the event of failure, adaptive morphology has proven to surpass control theory-based methods to recover functionality in some cases.[92,93]

Although there is a trade-off in the weight budget, new and creative ways to incorporate power transmission may solve coupled actuation in additive designs. In-depth studies of aerodynamic modeling can aid in this regard to find and tune the optimal topological parameters that improve performance on the ground and in the air. Active suspension increases controllability in both landing and ground locomotion phases and it is especially useful on uneven terrains.

5.4. Materials and Manufacturing

Structures that leverage novel materials that deform in response to mechanical, thermal, chemical, and electromagnetic stimuli[94–96] can be used to optimize weight, yield stress, and aerodynamics all contributing to performance. Robots consisting of soft bodies made up of compliant materials are part of an emerging field of technology called soft robotics.[97] Their ability to deform invariant of pose and shape enables them to adapt to external environment and may potentially improve performance in complex tasks involving unstructured and unknown terrains. Moreover, soft machines are safer to interact with living agents such as humans. However, designing these continuum materials, often with rigid backbones poses a new set of problems in modeling and control. Optimizing design parameters can exploit embodied intelligence as the research in this field progresses, opening new possibilities for multimodal robots. Manufacturing concepts such as composite fabrication, Japanese paper-folding technique origami and kirigami, tensegrity structures (which can act as enclosures), meta-materials,[98] multidimensional and multimaterial printing,[99] biofabrication, and tissue engineering can be combined with material technology to improve load-bearing capacity, high compliance, and programmable responses.[100]

5.5. Mechatronics

Limitations in energy storage and dissipation, latency, electronics' resolution, and bandwidth pose a challenge in mechatronic integration for multimodality. Novel actuators such as piezoelectric actuators, ultrasonic motors, voice coils, shape memory alloys, and micro-electromechanical systems also known as MEMS and electroactive polymers[101] address some of these common problems. The integration of lightweight actuators that behave as sensorized robotic skins and artificial muscles can result in better signal resolution, frequency response, and energy management overall. Redundancy in sensing and actuation can improve sensorial and locomotion assets in the transient phases. Embodied and distributed actuation and sensing can favor size and weight and become especially useful in smaller-scale vehicles.

5.6. Modeling

Although there has been plenty of research that tackles the dynamic modeling of unmanned aerial vehicles and ground mobile robots, understanding dynamic coupling in multimodal robots can be tricky. Mathematical modeling extends to applications that involve robot–environment interactions. How do we model the dynamics in contact-prone operations in unstructured environments? Methodologies to model multiple modalities typically start from the interrelations of existing separate models of each mode. More complex transient dynamics between two modes require understanding of physical interaction and implementation of synchronous control of different components. The main challenge that prevents field readiness of multimodal robots lays in robustness of systems. One possibility is linear translation in any direction using simultaneous navigation or motion of limbs.[102] Naturally, bioinspiration can be a theme of multimodality.

5.7. Control

Embodied physical intelligence is a challenge incorporated into mechanical and material designs in fabricating robots. Collision tolerance is one way to decrease the risk of hardware failure. Having compliance in the bodies and landing gears of these multimodal robots allows better impact absorption. These concepts enhance the longevity of the robots, however, a complex design does not necessarily mean failure susceptibility. Control is crucial in directing behavior and combining multiple agents in swarms in a reliable and safe way, especially if there are human interactions. To this end, considering environmental interactions, failure mode risks, and agile behavior is needed in designing locomotion schemes and transformation to adapt to different tasks. Obstacles can emerge from unseen objects and robust control responses to natural disturbances such as wind, heat, and humidity are needed. These risks are not only directed to the robot but also to the interaction or inspection target. Handling this becomes crucial because drones and other agents, possibly a human, usually interacts in the field. A line of research that deals with events such as mechanical failure like propeller loss[103] can be integrated. Directing behavior includes closed-loop trajectory tracking, especially in complete enclosure drones, and motion and path planning, for example, the prevention of gimbal locks, common in prototypes that utilize gimbals or more generally to robots that have linkages such as in limbs and legs.[60] How do we improve speed, response, and agility, possibly by fusing with improving perception?

5.8. Manipulation and Teleoperation

To deploy field-ready unmanned aerial vehicles (UAVs), understanding the interaction between the robot and the environment is crucial to successfully perform tasks. In many of the application cases above, nondestructive manipulation is critical while the drone interacts with objects. This goes with teleoperation or even autonomous navigation in interacting in contact-prone field environments. In animals, arms, limbs, and legs used for locomotion are also used for foraging for food. Extended limb formation is embodied with patagia or flapping mechanisms such as handling wings, thereby, manipulation and locomotion are in synergy and integrated. However, in multimodal robots, this is not the case. For instance, a multimodal robot[104] features separate actuators for grasping and for precise locomotion. Moreover, multivehicle combinations used teleoperation extensively to achieve cooperation in performing tasks.[11,12]

5.9. Performance Metrics and Evaluation Methods

While we can isolate locomotion modes and evaluate them separately, a commonly accepted metric for assessing the robustness of transition phases is missing. Transients, however, play a key role in robustness and autonomy for field deployment.[65] The hovering capability of some propeller-based multimodal robots facilitates transients between different terrains and locomotion modalities. Further examples of how propellers have lessened the limitations of ground robots while moving on harsh terrains have also been shown, where thrust vectoring provides propulsion on high-friction surfaces.

Glide ratio (GR) is the ratio of horizontal distance and change in altitude. It is a common performance index in gliding robots. A gliding–climbing robot achieved a measured GR of 2,[105] not far from rodents such as the Lord Derby's anomalure and Northern flying squirrel with GRs of 2.2 and 2.4, respectively. Another common metric for coupled multimodal robots is the mass integration metric, i.e., the ratio of the sum of the aerial locomotion and terrestrial locomotion components, and the total mass of the robot. Thrust-to-weight ratio, usually applied to single-mode robots, is also applied as a propulsion index to actuators in multiple modes.

Throughout the reviewed works, traditional benchmarking approaches have been widely reported in literature qualifying the cost of transport and task performance including transition, trajectory, robustness, and other abilities. Practical approaches in robophysics applied to experimentation[8] can be another tool to benchmark the locomotion of robots with embodiment and self-organization.[106] Dynamic quantification and control continually benefit from numerical approaches, optimization, statistics, and machine learning.

Accurate system identification, high-fidelity modeling, and closed-loop control are key elements for success in real-world deployment, especially in locomotion transients. Failure can be further mitigated by extensive validation campaigns in the field, with results directly feeding into design and control optimization cycles or data-driven learning methods.

6. Conclusion: Toward Deploying Multimodal Robots in the Real World

The performance disparity between nature and robotics is substantial and is directly tied to the time and effort allocated by designers and engineers for technological advancement. However, it may help to bring into perspective how long nature has been evolving, time has given nature the advantage of millions of mistakes and iterations encompassed in evolution, as described by Charles Darwin. Nature, in all its intricacy, has symbiotically integrated physical and cognitive intelligence, synthesizing responses to external stimuli and environmental factors over millions of years. Nature's complexity is so profound that many of its fundamental processes remain incompletely understood, within the realm of biology. Robotics plays a pivotal role in advancing our understanding through the field of robotics-inspired biology, where bioinspired machines are observed to quantify metrics of artificial systems and translate them to principles of living organisms. Adaptation or metamorphosis has been an overarching theme in the latest developments in robotics. We have seen that in multimodal robots, approaches to achieve this can be additive and adaptive in monolithic drones. Both start with an application in mind. For instance, for inspection, it may be that robots require functionalities such as rolling on ceilings or wall climbing. The basis of designs in this approach is the addition of two or more well-established fields of ground robotics and aerial robotics. The key insight in mechanical design is in the actuator coupling that may be partial or complete. Integrating concepts from both robotic fields can be inspired by biology, as to how animal transitions between two modes. This supports the fact that many of the publications that contain additive multimodal prototypes are progressing fast through control engineering. Once mechanical prototypes are fabricated and then controlled, the time it takes to deploy these for testing in real-world scenarios is relatively short. Additionally, since iteration time for control development is faster than in mechanical development, additive approach multimodal robots can have reliability that translates to Technological Readiness Levels[107] in less time. The intelligence embedded in these robots translates to adaptation in the test scenarios, hence adaptation to the environment. The adaptive approach is commonly bioinspired and as suggested by Kovač et al.,[108] curiosity-driven. Taking inspiration from well-developed organism morphology, form informs function. Designs can take insights from the morphological adaptation of different species of animals along the phylogeny. Metamorphosis[109] or the adaptation of biological organisms in their lifetime for survival can analogously be applied to changing structures and forms of prototypes in robotics. This results in the reconfiguration of morphing metamorphic structures. Robot functionalities have the possibility to have a wider creative breadth. Field readiness for adaptive approach-based multimodal robots may take more time and resources but the potential that the mechanical complexity can further enhance computational intelligence is huge.

Human-made developments have demonstrated remarkable ingenuity, evolving at an accelerated pace since the inception of robotics. Designers draw inspiration from the intricacies of both biological organisms and machine-metamorphic robotic

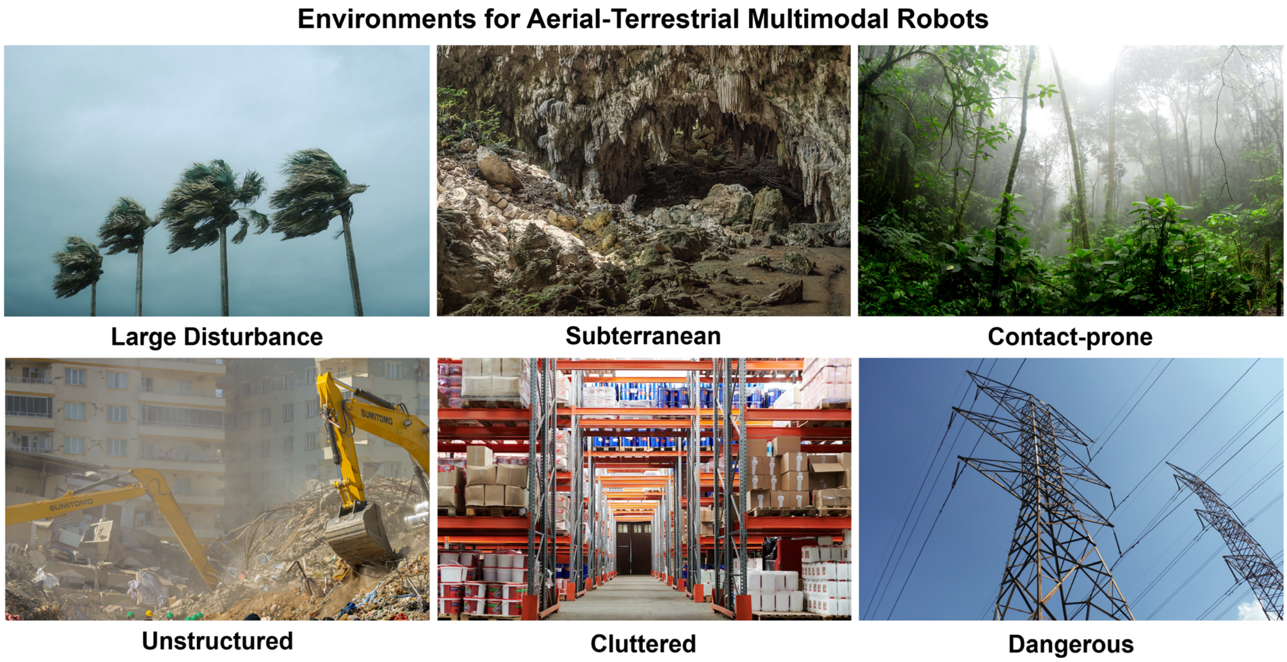

Figure 4. Challenging environments in the natural and man-made world that multimodal aerial–terrestrial robots can tackle. All figures retrieved from the Pexels website (www.pexels.com), published under the Creative Commons Zero (CC0) license.

systems characterized by soft bodies. Consequently, the ongoing advancement of material science is poised to propel robotics into new realms of development. The simplification of the design and manufacturing processes remains a primary catalyst in achieving readiness for various fields and enhancing computational efficiency, particularly in complex scenarios. Achieving multiple functionalities necessitates the synergy of diverse disciplines and technologies, fostering collaborative endeavors (see Appendix) that yield innovative solutions. We anticipate that these emerging technologies will address challenging environments illustrated in **Figure 4**, which currently pose significant hurdles for robots. These environments encompass scenarios where flying and anchoring robots can effectively stabilize and maneuver in large weather-induced disturbances. Furthermore, they involve robots capable of thriving in dangerous settings by flying, perching, and climbing, with potential for human–robot interaction. Insect-inspired swarms of robots are poised to excel in tasks involving navigation, localization, and intercommunication. Biodegradable and retrievable grasping flying robots hold promise for physical contact-based operations in densely forested areas, actively preventing wildfires and illegal activities. Additionally, high-payload acrobatic flying robots will perform precise, high-speed trajectories safely alongside factory workers. Night vision-equipped aerial–terrestrial robots will likely manage complex tasks, even in subterranean caves or mines.

Appendix

The database of the citations of the reviewed publications are available at https://github.com/BioMorphic-Intelligence-Lab/Aerial-Terrestrial-Multimodal-Robots. In order to keep the list updated, we encourage researchers to contribute by submitting a form in the *Request to Add Publication* tab.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

aerial–terrestrial locomotion, embodied intelligence, multifunctional aerial robots, multimodal robots

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[1] A. A. Biewener, S. N. Patek, *Animal Locomotion*, 2nd ed., Oxford University Press, Oxford, United Kingdom **2018**, https://doi.org/10.1093/oso/9780198743156.001.0001.
[2] F. Rubio, F. Valero, C. Llopis-Albert, *Int. J. Adv. Rob. Syst.* **2019**, *16*, https://doi.org/10.1177/1729881419839596.
[3] L. Daler, *Ph.D. Thesis*, EPFL (Lausanne) **2015**, https://www.epfl.ch/labs/lis/research/completed/daler-2/.
[4] M. Hassanalian, A. Abdelkefi, *Prog. Aerosp. Sci.* **2017**, *91*, 99.
[5] R. J. Lock, S. C. Burgess, R. Vaidyanathan, *Bioinspiration Biomimetics* **2014**, *9*, 011001.
[6] M. Calisti, G. Picardi, C. Laschi, *J. R. Soc. Interface* **2017**, *14*, 20170101.

[7] C. S. X. Ng, M. W. M. Tan, C. Xu, Z. Yang, P. S. Lee, G. Z. Lum, *Adv. Mater.* **2021**, *33*, 2003558.
[8] J. Aguilar, T. Zhang, F. Qian, M. Kingsbury, B. McInroe, N. Mazouchova, C. Li, R. Maladen, C. Gong, M. Travers, R. L. Hatton, H. Choset, P. B. Umbanhowar, D. I. Goldman, *Rep. Prog. Phys.* **2016**, *79*, 110001.
[9] R. C. Michelson, US6082671A, **2000**.
[10] A. Kossett, R. D'Sa, J. Purvey, N. Papanikolopoulos, in *2010 IEEE Int. Conf. on Robotics and Automation*, IEEE, Piscataway, NJ **2010**, pp. 632–637, https://ieeexplore.ieee.org/abstract/document/5509453.
[11] K. Nagatani, K. Akiyama, G. Yamauchi, H. Otsuka, T. Nakamura, S. Kiribayashi, K. Yoshida, Y. Hada, S. Yuta, K. Fujino, T. Izu, R. Mackay, in *2013 IEEE Int. Symp. on Safety, Security, and Rescue Robotics*, IEEE, Piscataway, NJ **2013**, pp. 1–6, https://ieeexplore.ieee.org/document/6719324.
[12] S. Latscha, M. Kofron, A. Stroffolino, L. Davis, G. Merritt, M. Piccoli, M. Yim, in *2014 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, IEEE, Piscataway, NJ **2014**, pp. 1868–1873, https://ieeexplore.ieee.org/document/6942808, ISSN: 2153-0866.
[13] R. Zufferey, R. Siddall, S. F. Armanini, M. Kovac, *Between Sea and Sky: Aerial Aquatic Locomotion in Miniature Robots*, volume 29 of Biosystems & Biorobotics, Springer International Publishing, Cham **2022**.
[14] Y. Tan, B. Chen, *Unmanned Syst.* **2021**, *9*, 263.
[15] K. Ren, J. Yu, *Ocean Eng.* **2021**, *227*, 108862.
[16] A. Ijspeert, *Annu. Rev. Control Rob. Auton. Syst.* **2020**, *3*, 173.
[17] J. Guo, K. Zhang, S. Guo, C. Li, X. Yang, in *2019 IEEE Int. Conf. on Mechatronics and Automation*, IEEE, Piscataway, NJ **2019**, pp. 1508–1513, https://ieeexplore.ieee.org/document/8816501, ISSN: 2152-744X.
[18] L. Daler, S. Mintchev, C. Stefanini, D. Floreano, *Bioinspiration Biomimetics* **2015**, *10*, 016005.
[19] G.-P. Jung, C. S. Casarez, S.-P. Jung, R. S. Fearing, K.-J. Cho, in *2016 IEEE Int. Conf. on Robotics and Automation*, IEEE, Piscataway, NJ **2016**, pp. 4680–4685.
[20] F. J. Boria, R. J. Bachmann, P. Ifju, R. D. Quinn, R. Vaidyanathan, C. Perry, J. Wagener, in *IEEE/RSJ Inter. Conf. on Intelligent Robots and Systems*, IEEE, Piscataway, NJ **2005**, pp. 3959–3964, https://ieeexplore.ieee.org/abstract/document/1545597.
[21] P. Ifju, D. Jenkins, S. Ettinger, Y. Lian, W. Shyy, M. Waszak, in *40th AIAA Aerospace Sciences Meeting & Exhibit*, American Institute of Aeronautics and Astronautics, Reno, NV, USA **2002**, https://arc.aiaa.org/doi/abs/10.2514/6.2002-705.
[22] R. Quinn, J. Offi, D. Kingsley, R. Ritzmann, in *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, Vol. *3*, IEEE, Piscataway, NJ **2002**, pp. 2652–2657, https://ieeexplore.ieee.org/abstract/document/1041670.
[23] M. Fremerey, S. Köhring, O. Nassar, M. Schöne, K. Weinmeister, F. Becker, G. S. Đorđević, H. Witte, in *Biomimetic and Biohybrid Systems* (Eds: A. Duff, N. F. Lepora, A. Mura, T. J. Prescott, P. F. M. J. Verschure), Lecture Notes in Computer Science, Springer International Publishing, Cham **2014**, pp. 97–107, ISBN 978-3-319-09435-9, https://link.springer.com/chapter/10.1007/978-3-319-09435-9_9.
[24] R. J. Bachmann, F. J. Boria, R. Vaidyanathan, P. Ifju, R. D. Quinn, *Mech. Mach. Theory* **2008**, *44*, 513.
[25] R. J. Bachmann, R. Vaidyanathan, R. D. Quinn, in *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, IEEE, St. Louis, MO **2009**, pp. 5647–5652, https://ieeexplore.ieee.org/document/5354102.
[26] J. Dickson, C. Kulinka, M. Martin, J. Yeol, J. Clark, in *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, American Institute of Aeronautics and Astronautics, Orlando, FL **2011**, ISBN 978-1-60086-950-1, https://arc.aiaa.org/doi/10.2514/6.2011-1283.
[27] D. I. Goldman, T. S. Chen, D. M. Dudek, R. J. Full, *J. Exp. Biol.* **2006**, *209*, 2990.
[28] J. D. Dickson, J. D. Dickson, J. E. Clark, *IEEE/ASME Trans. Mechatron.* **2013**, *18*, 494.
[29] C. J. Pratt, K. K. Leang, in *2016 IEEE Int. Conf. on Robotics and Automation (ICRA)*, IEEE, Piscataway, NJ **2016**, pp. 3267–3274, https://ieeexplore.ieee.org/document/7487498.
[30] K. Kim, P. Spieler, E.-S. Lupu, E. S. Lupu, A. Ramezani, S.-J. Chung, *Sci. Rob.* **2021**, *6*, 59.
[31] M. Ceccarelli, D. Cafolla, M. Russo, G. Carbone, in *Advances in Service and Industrial Robotics* (Eds: C. Ferraresi, G. Quaglia), Mechanisms and Machine Science, Springer International Publishing, Cham **2018**, pp. 355–362, ISBN 978-3-319-61276-8, https://link.springer.com/chapter/10.1007/978-3-319-61276-8_39.
[32] M. Pitonyak, F. Sahin, in *12th System of Systems Engineering Conf.*, IEEE, Waikoloa, HI **2017**, pp. 1–6, https://ieeexplore.ieee.org/document/7994965.
[33] Y. Sun, Z. Jing, D. Peng, W. Chen, J. Huang, in *IEEE Int. Conf. on Advanced Robotics and Mechatronics (ICARM)*, IEEE, Chongqing, China **2021**, https://ieeexplore.ieee.org/document/9536074.
[34] G. Zhong, J. Cao, X. Chai, Y. Bai, *IEEE Access* **2021**, *9*, 10871.
[35] Y. Mulgaonkar, B. Araki, J.-S. Koh, L. Guerrero-Bonilla, D. M. Aukes, A. Makineni, M. T. Tolley, D. Rus, R. J. Wood, V. Kumar, in *2016 IEEE Int. Conf. on Robotics and Automation (ICRA)*, IEEE, Piscataway, NJ **2016**, pp. 4672–4679, https://ieeexplore.ieee.org/document/7487667.
[36] C. Hui, L. Liu, D. R. Romano, Y. Zhou, D. R. Romano, X. Deng, Z. Tu, *IEEE Rob. Autom. Lett.* **2021**, *6*, 7549.
[37] D. Floreano, R. J. Wood, *Nature* **2015**, *521*, 460.
[38] Y. M. Chukewad, J. M. James, A. T. Singh, S. B. Fuller, *IEEE Trans. Rob.* **2021**, *37*, 2025.
[39] K. C. Peterson, K. Peterson, R. S. Fearing, in *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, IEEE, Piscataway, NJ **2011**, pp. 5080–5086, https://ieeexplore.ieee.org/abstract/document/6095041.
[40] K. C. Peterson, K. Peterson, P. M. Birkmeyer, R. Dudley, R. S. Fearing, *Bioinspiration Biomimetics* **2011**, *6*, 046008.
[41] C. J. Salaan, K. Tadakuma, Y. Okada, Y. Sakai, K. Ohno, S. Tadokoro, *IEEE Rob. Autom. Lett.* **2019**, *4*, 2568.
[42] J. Yang, Y. Zhu, L. Zhang, L. Zhang, Y. Dong, Y. Ding, *IEEE Rob. Autom. Lett.* **2022**, *7*, 9199.
[43] H. C. Choi, I. Wee, M. Corah, S. Sabet, T. Kim, T. Touma, D. H. Shim, A.-a. Agha-mohammadi, *Springer Exp. Rob.* **2021**, *19*, 60.
[44] J. R. Page, P. E. I. Pounds, In *2014 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, IEEE, Piscataway, NJ **2014**, pp. 4834–4841, https://ieeexplore.ieee.org/document/6943249, ISSN: 2153-0866.
[45] T. Dias, M. Basiri (Preprint) arXiv:2303.01933, v1, Submitted: Mar. **2023**.
[46] M. Ootsuka, C. Premachandra, K. Kato, in *2014 Joint 7th Int. Conf. on Soft Computing and Intelligent Systems and 15th Int. Symp. on Advanced Intelligent Systems*, Kitakyushu, Japan **2014**, pp. 1470–1474, https://ieeexplore.ieee.org/document/7044710.
[47] S. Mishra, K. Patnaik, Y. Garrard, Z. Chase, M. Ploughe, W. Zhang, in *2020 IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics*, IEEE, Piscataway, NJ **2020**, pp. 1270–1275, https://ieeexplore.ieee.org/abstract/document/9158943.
[48] B. Araki, J. Strang, S. Pohorecky, C. Qiu, T. Naegeli, D. Rus, in *IEEE Int. Conf. on Robotics and Automation*, IEEE, Singapore **2017**, https://ieeexplore.ieee.org/document/7989657.

[49] M. Pimentel, M. Basiri, *IEEE Rob. Autom. Lett.* **2022**, *7*, 5135.
[50] D. D. Fan, R. Thakker, T. Bartlett, M. B. Miled, L. Kim, E. Theodorou, A.-a. Agha-mohammadi, in *2019 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*, IEEE, Piscataway, NJ **2019**, pp. 3070–3077, https://ieeexplore.ieee.org/document/8968276, ISSN: 2153-0866.
[51] M. Itasse, J.-M. Moschetta, Y. Ameho, R. Carr, *Int. J. Micro Air Veh.* **2011**, *3*, 229.
[52] D. Zhang, C. Guo, H. Ren, P. Zhu, M. Xu, H. Lu, in *IEEE Int. Conf. on Real-time Computing and Robotics*, IEEE, Xining, China **2021**, pp. 393–398, https://ieeexplore.ieee.org/document/9517607.
[53] Y. Wang, N. Zhang, B. Pan, B. Su, S. Li, in *2021 China Automation Congress*, Beijing, China **2021**, pp. 7751–7756, https://ieeexplore.ieee.org/document/9727502, ISSN: 2688-0938.
[54] K. Tanaka, D. Zhang, S. Inoue, R. Kasai, H. Yokoyama, K. Shindo, K. Matsuhiro, S. Marumoto, H. Ishii, A. Takanishi, in *2017 IEEE Int. Conf. on Mechatronics and Automation (ICMA)*, IEEE, Piscataway, NJ **2017**, pp. 1503–1508, https://ieeexplore.ieee.org/document/8016039.
[55] C. Premachandra, M. Otsuka, in *IEEE Inter. Systems Engineering Symp. (ISSE)*, IEEE, Piscataway, NJ **2017**, p. 8088328, https://ieeexplore.ieee.org/document/8088328.
[56] A. Kalantari, T. Touma, L. Kim, R. Jitosho, K. Strickland, B. T. Lopez, A.-A. Agha-Mohammadi, in *IEEE Aerospace Conf.*, IEEE, Big Sky, MT **2020**, pp. 1–10, https://ieeexplore.ieee.org/document/9172782.
[57] B. Li, L. Ma, D. Wang, Y. Sun, *IET Cyber-Syst. Robot.* **2021**, *3*, 103.
[58] S. Kaneki, S. Yokota, D. Chugo, H. Hashimoto, in *2018 IEEE Int. Conf. on Industrial Technology*, IEEE, Piscataway, NJ **2018**, pp. 1961–1966, https://ieeexplore.ieee.org/document/8352487.
[59] A. Kalantari, M. Spenko, in *2013 IEEE Int. Conf. on Robotics and Automation*, IEEE, Piscataway, NJ **2013**, pp. 4445–4450, https://ieeexplore.ieee.org/document/6631208.
[60] A. Briod, P. Kornatowski, J.-C. Zufferey, D. Floreano, *J. Field Rob.* **2014**, *31*, 496.
[61] S. Mizutani, Y. Okada, C. J. Salaan, T. Ishii, K. Ohno, S. Tadokoro, in *2015 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*, IEEE, Piscataway, NJ **2015**, pp. 1271–1278, https://ieeexplore.ieee.org/abstract/document/7353532.
[62] M. Yamada, M. Nakao, Y. Hada, N. Sawasaki, in *2017 Int. Conf. on Unmanned Aircraft Systems (ICUAS)*, Miami, FL, USA **2017**, pp. 1014–1021, https://ieeexplore.ieee.org/document/7991308.
[63] S. Atay, M. Bryant, G. Buckner, *J. Mech. Rob.* **2021**, *13*, 5.
[64] C. J. Dudley, A. C. Woods, K. K. Leang, in *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*, IEEE, Hamburg, Germany **2015**, pp. 5863–5869, https://ieeexplore.ieee.org/document/7354210.
[65] H. Jia, S. Bai, R. Ding, J. Shu, Y. Deng, B. L. Khoo, P. Chirarattananon, *IEEE/ASME Trans. Mechatron.* **2022**, *27*, 4741.
[66] K. Kawasaki, M. Zhao, K. Okada, M. Inaba, in *2013 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, IEEE, Piscataway, NJ **2013**, pp. 1880–1885, https://ieeexplore.ieee.org/document/6696605.
[67] Z. Zheng, J. Wang, Y. Wu, Q. Cai, H. Yu, R. Zhang, J. Tu, J. Meng, G. Lu, F. Gao, (Preprint) arXiv:2303.00668, v1, Submitted: Mar **2023**.
[68] S. Morton, N. Papanikolopoulos, in *2017 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*, IEEE, Piscataway, NJ **2017**, pp. 5149–5154, https://ieeexplore.ieee.org/document/8206402.
[69] X. Zhang, Y. Huang, K. Huang, X. Wang, D. Jin, H. Liu, J. Li (Preprint), arXiv:2210.16875, v1, Submitted: Oct 2022.
[70] N. Meiri, D. Zarrouk, in *Int. Conf. on Robotics and Automation (ICRA)*, IEEE, Montreal, QC **2019**, pp. 5302–5308, https://ieeexplore.ieee.org/document/8794260.
[71] N. B. David, D. Zarrouk, *IEEE Rob. Autom. Lett.* **2021**, *6*, 6188.
[72] D. Hwang, E. Barron III, A. Tahidul Haque, M. Bartlett, *Sci. Rob.* **2022**, *7*, 63.
[73] A. Miriyev, M. Kovač, *Nat. Mach. Intell.* **2020**, *2*, 658.
[74] E. Sihite, A. Kalantari, R. Nemovi, A. Ramezani, M. Gharib, *Nature Commun.* **2023**, *14*, 3323.
[75] A. Fabris, E. Aucone, S. Mintchev, *Adv. Intell. Syst.* **2022**, *4*, 2200113.
[76] A. Fabris, S. Kirchgeorg, S. Mintchev, in *IEEE Int. Symp. on Safety, Security and Rescue Robotics*, IEEE, Piscataway, NJ **2021**, https://ieeexplore.ieee.org/document/9597683.
[77] M. A. Woodward, M. Sitti, in *2011 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, IEEE, Piscataway, NJ **2011**, pp. 556–561, https://ieeexplore.ieee.org/document/6095108.
[78] M. A. Woodward, M. Sitti, *Int. J. Rob. Res.* **2014**, *33*, 1511.
[79] W. D. Shin, J.-J. Park, H.-W. Park, H. W. Park, in *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS)*, IEEE, Piscataway, NJ **2018**, pp. 8158–8164, https://ieeexplore.ieee.org/document/8594210.
[80] A. Vidyasagar, J.-C. Zufferey, D. Floreano, M. Kovač, *Bioinspiration Biomimetics* **2015**, *10*, 025006.
[81] C. Vourtsis, W. J. Stewart, W. J. Stewart, D. Floreano, *IEEE Rob. Autom. Lett.* **2021**, *7*, 223.
[82] C. Schlenoff, E. Messina, in *Proc. of the 2005 ACM Workshop on Research in Knowledge Representation for Autonomous Systems (KRAS '05)*, Association for Computing Machinery, New York, NY **2005**, pp. 27–34, ISBN 978-1-59593-202-0, https://dl.acm.org/doi/10.1145/1096961.1096965.
[83] N. Michael, S. Shen, K. Mohta, V. Kumar, K. Nagatani, Y. Okada, S. Kiribayashi, K. Otake, K. Yoshida, K. Ohno, E. Takeuchi, S. Tadokoro, in *Field and Service Robotics: Results of the 8th Int. Conf., Springer Tracts in Advanced Robotics* (Eds: K. Yoshida, S. Tadokoro), Springer, Berlin, Heidelberg **2014**, pp. 33–47, ISBN 978-3-642-40686-7, https://doi.org/10.1007/978-3-642-40686-7_3.
[84] C. J. Rose, P. Mahmoudieh, R. S. Fearing, in *2015 IEEE Int. Conf. on Robotics and Automation (ICRA)*, IEEE, Piscataway, NJ **2015**, pp. 4029–4035, https://ieeexplore.ieee.org/document/7139762, ISSN: 1050-4729.
[85] A. Agha-mohammadi, A. Tagliabue, S. Schneider, B. Morrell, M. Pavone, J. D. Hofgartner, I. Nesnas, K. Carpenter, R. Amini, A. Kalantari, A. Babuscia, J. Bayandor, J. I. Lunine, *The Shapeshifter: a Morphing, Multi-Agent, Multi-Modal Robotic Platform for the Exploration of Titan*, California Insitute of Technology **2020**, https://ntrs.nasa.gov/api/citations/20190033457/downloads/20190033457.pdf.
[86] J. Hughes, A. Abdulali, R. Hashem, F. Iida, *IOP Conf. Ser.: Mater. Sci. Eng.* **2022**, *1261*, 012001.
[87] G. C. H. E. de Croon, J. J. G. Dupeyroux, C. De Wagter, A. Chatterjee, D. A. Olejnik, F. Ruffier, *Nature* **2022**, *610*, 485.
[88] E. Chang, L. Y. Matloff, A. K. Stowers, D. Lentink, *Sci. Rob.* **2020**, *5*, eaay1246, https://www.science.org/doi/full/10.1126/scirobotics.aay1246.
[89] N. F. M. Roozenburg, J. Eekels, *Product Design: Fundamentals and Methods*, A Wiley Series in Product Development, Wiley, Chichester, New York **1995**.
[90] *Springer Handbook of Robotics* (Eds: B. Siciliano, O. Khatib), Springer, Berlin **2008**, ISBN: 978-3-540-23957-4.
[91] A. Kalantari, M. Spenko, *American Society of Mechanical Engineers Digital Collection*, **2012**, pp. 1067–1072, https://asmedigitalcollection.asme.org/IDETC-CIE/proceedings-abstract/IDETC-CIE2012/45035/1067/255811.
[92] S. Kriegman, S. Walker, D. S. Shah, M. Levin, R. Kramer-Bottiglio, J. Bongard, in *Proc. of Robotics: Science and Systems*, Vol. *15*, MIT Press Journals, Freiburg im Breisgau, Germany **2019**, ISBN 978-0-9923747-5-4, http://www.roboticsproceedings.org/rss15/p28.html.

[93] A. Seilacher, *Syst. Zool.* **1973**, *22*, 451.
[94] Y. Xia, Y. He, F. Zhang, Y. Liu, J. Leng, *Adv. Mater.* **2021**, *33*, 2000713.
[95] M. Bashir, P. Rajendran, *J. Intell. Mater. Syst. Struct.* **2018**, *29*, 3681.
[96] S. Gantenbein, K. Masania, W. Woigk, J. P. W. Sesseg, T. A. Tervoort, A. R. Studart, *Nature* **2018**, *561*, 226.
[97] D. Rus, M. T. Tolley, *Nature* **2015**, *521*, 467.
[98] K. Bertoldi, V. Vitelli, J. Christensen, M. van Hecke, *Nat. Rev. Mater.* **2017**, *2*, 17066, https://www.nature.com/articles/natrevmats201766.
[99] R. L. Truby, J. A. Lewis, *Nature* **2016**, *540*, 371.
[100] Y. Tang, G. Lin, S. Yang, Y. K. Yi, R. D. Kamien, J. Yin, *Adv. Mater.* **2017**, *29*, 1604262.
[101] S. Singh, M. Zuber, M. N. Hamidon, N. Mazlan, A. A. Basri, K. A. Ahmad, *Prog. Aerosp. Sci.* **2022**, *132*, 100833.
[102] P. Ratsamee, P. Kriengkomol, T. Arai, K. Kamiyama, Y. Mae, K. Kiyokawa, T. Mashita, Y. Uranishi, H. Takemura, in *2016 IEEE Inter. Symp. on Safety, Security, and Rescue Robotics (SSRR)*, **2016**, pp. 62–67, https://ieeexplore.ieee.org/document/7784278.
[103] M. W. Mueller, R. D'Andrea, In *2014 IEEE Inter. Conf. on Robotics and Automation (ICRA)*, IEEE, Piscataway, NJ **2014**, pp. 45–52, https://ieeexplore.ieee.org/document/6906588, ISSN: 1050-4729.
[104] S. Mishra, D. Yang, C. Thalman, P. Polygerinos, W. Zhang, *Design and Control of a Hexacopter With Soft Grasper for Autonomous Object Detection and Grasping*, American Society of Mechanical Engineers, Atlanta, GA, USA **2018**, https://asmedigitalcollection.asme.org/DSCC/proceedings-abstract/DSCC2018/51913/270951.
[105] J. W. Bahlman, S. M. Swartz, D. K. Riskin, K. S. Breuer, *J. R. Soc. Interface* **2013**, *10*, 20120794.
[106] R. Pfeifer, M. Lungarella, F. Iida, *Science* **2007**, *318*, 1088.
[107] M. Héder, *Innovation J.* **2017**, *22*, 1.
[108] M. Kovač, J.-C. Zufferey, D. Floreano, in *Flying Insects and Robots* (Eds: D. Floreano, J.-C. Zufferey, M. V. Srinivasan, C. Ellington), Springer, Berlin, Heidelberg **2010**, pp. 271–284, ISBN 978-3-540-89393-6, https://doi.org/10.1007/978-3-540-89393-6_19.
[109] P. H. Nguyen, M. Kovač, *IOP Conf. Ser.: Mater. Sci. Eng.* **2022**, *1261*, 012006.

Jane Pauline Ramirez is a licensed engineer with multidisciplinary expertise in bionics engineering and mechanical engineering and international research experiences in the Philippines, Japan, Italy, Switzerland, and the Netherlands. Her mission is to design and develop inclusive and socially accessible systems, synergized excellently with nature, that positively impact communities. Currently, she is a Ph.D. candidate in aerospace engineering at the Biomorphic Intelligence Laboratory under the supervision of Prof. Salua Hamaza at the Delft University of Technology. She is interested in bioinspired design, embodied intelligence, multimodal locomotion, metamaterials, and compliant and smart systems.

Salua Hamaza is an assistant professor in Aerial Robotics and Director of the BioMorphic Intelligence Lab at TU Delft, Netherlands. Her research focuses on the development of aerial robots capable of physical interaction with the surroundings. Her robotic solutions take inspiration from biology for flying and interaction tasks, leveraging compliance in hardware and software to advance aerial robots' autonomy and versatility. She was Post-Doc at Imperial College London and obtained her Ph.D. in robotics and autonomous systems from the University of Bristol. She was also a researcher at the University of Seville, Spain, and the University of Twente, Netherlands. She received her M.Sc. in robotics jointly from the University of Bologna and TU Delft.

